Integrated Circuits and Applications
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Characteristics of Practical Operational Amplifier
Lecture – 10
AC Characteristics (Compensation Techniques and Slew Rate)

Ok. In this lecture we will discuss External Compensation Techniques. There are two external compensation techniques one is dominant pole compensation and second one is pole zero compensation. First, I will consider the dominant pole compensation. Let A is the uncompensated transfer function, this is A uncompensated transfer function with input v_i and let us call this outputs as A, let us call this output as $v_o{}'$. Then externally we are going to connect a RC network which provides a dominant pole and this is the final output v_o. So, if I assume that A' is the transfer function of the compensator network. So, this is given by $\frac{v_o}{v_i}$, this overall system and A is the transfer function of uncompensated system this is given by this output by this input.

First, I will find out the relation between this $v_o{}'$ and v_o. What is v_o in terms of $v_o{}'$? This is voltage division this in Laplace transform you can write down this one as $\frac{1}{SC}$. So, this is v_o this is $v_o{}'$ this is v_o. So, what is v_o? $v_o{}'\frac{\frac{1}{SC}}{R+\frac{1}{\frac{1}{SC}}}$.

So, this is equal to SC SC will get cancelled. So, $\frac{1}{1+SRC}v_0{}'$, but I want A'. So, if I want $A'=\frac{v_o}{v_i}$, this is equal to in terms of A what will be this value $v_o' = Av_i$ or $v_i=\frac{v_o{}'}{A}$. So, from this $v_i=\frac{v_o{}'}{A}$, A is uncompensated transfer function. If I substitute this v_i here, so, you will get a $v_o=\frac{A}{v_o{}'}$.

So, what is $\frac{v_o}{v_o{}'}$ from here? $\frac{1}{1+SRC}$. So, this is equal to A times $\frac{v_o}{v_o{}'}$ is this $\frac{1}{1+SRC}$. This is the expression for the transfer function of compensator network. Here A is the transfer function of the system. So, that may consisting of any number of break frequencies.

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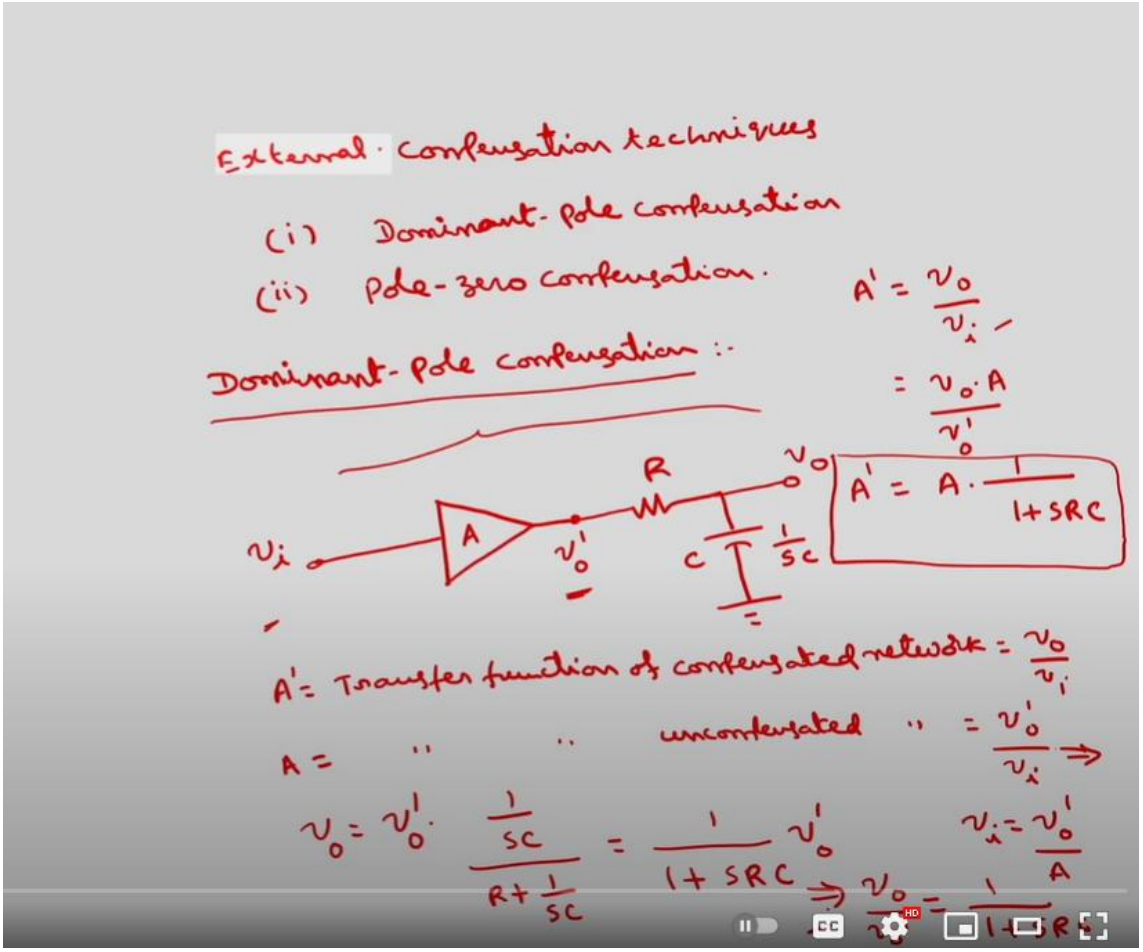

If I assume that the system is having 3 break frequencies, then we have written the expression for the A as $A = \frac{A_{OL}}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$,under whose frequency response we have plotted as this is $20dB/dec$, this is another $20dB/dec$, this is another $20dB/dec$. This is your f_1, f_2, this is f_3, this is $20dB/dec$ $-40dB/dec$, this is $-60dB/dec$. This is the frequency response of uncompensated network. Now, with compensation how this frequency response will be modified? For that if I substitute this A in the expression that you have obtained for the $A' = A\frac{A_{OL}}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})} = \frac{A_{OL}}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}\frac{1}{1+SRC}$.

So, this SRC can be written as $1 + SRC = 1 + j\omega RC = 1 + j2\pi fRC$. So, if I assume this $\frac{1}{2\pi fRC} = f_d$, this will be $1 + j\frac{f}{f_d}$, where $f_d = \frac{1}{2\pi fRC}$ is called dominant pole or dominant frequency. So, therefore, what happens to this A'? $\frac{A_{OL}}{(1+j\frac{f}{f_d})(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$. Here $f_d < f_1 < f_2 < f_3$. This is f_1, f_2, f_3, f_d will be somewhere before this f_1.

So, I will write somewhere here f_d. Then the compensated network will have frequency response. So, instead of having $-20dB$, $-40dB$, $-40dB$. So, we have only $-20dB/dec$ up to f_1. This is the frequency response of compensated frequency network.

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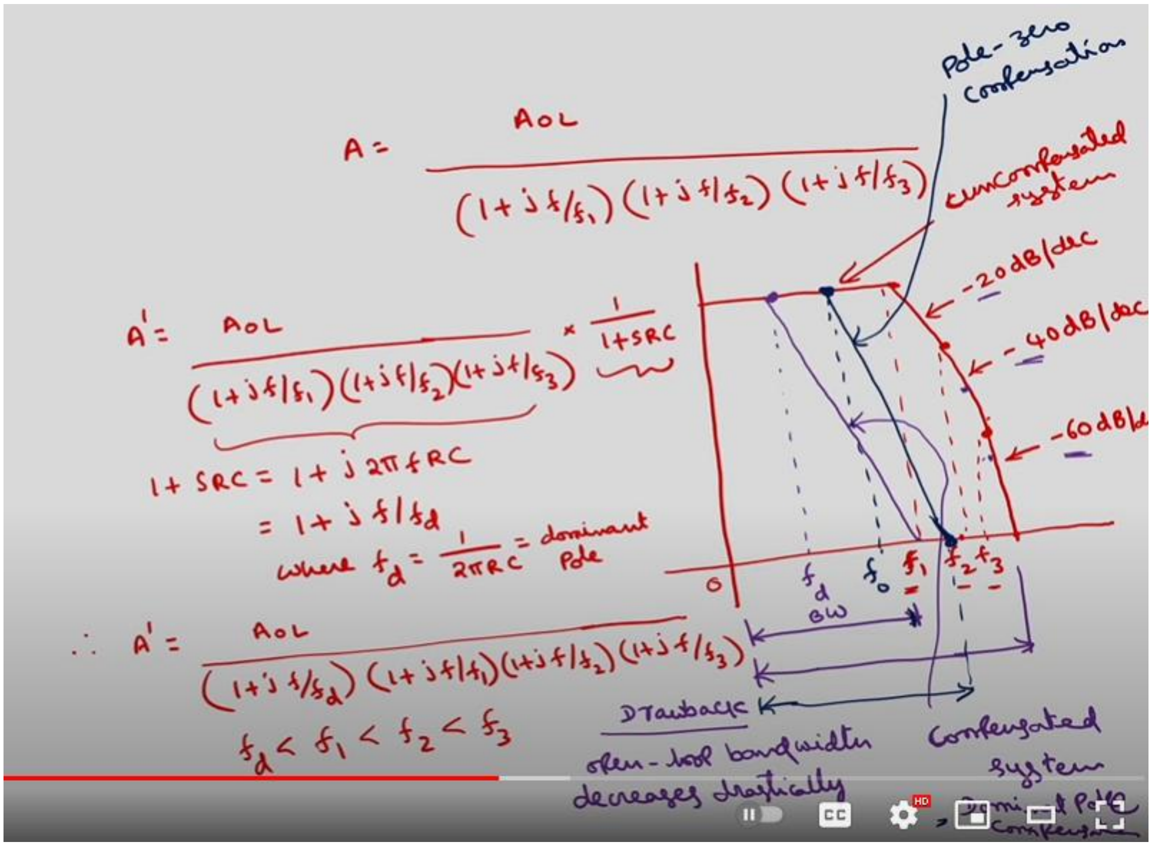

This is the frequency response of compensated network. So, we can avoid the problem with the uncompensated network, where there is a possibility of instability if the gain is somewhere here or here that I have described in the previous slides. Now, we can avoid that problem by providing a dominant pole, but the drawback of this type of compensation technique is now the bandwidth will be this much. Previously the bandwidth was without compensation this was the bandwidth. Now, bandwidth has been decreased.

So, the open loop bandwidth decreases drastically. This is the drawback of the dominant pole compensation technique. So, to avoid this drawback we have the second technique called as pole zero compensation. So, as the name implies we are going to introduce one pole and one zero at the output of uncompensated operational amplifier circuit. The uncompensated circuit v_i and let us call this output as $v_o{}'$.

And here instead of having just simply as resistor and capacitor we will be having two resistor and one capacitor this is V0 final output. Let us call this one as R_1, R_2, C_2. This you can call as Z_2, this you can call as Z_1 in terms of impedances. Now, what will be expression for this transfer function of the compensated network A'? We can derive in a similar manner $A' = \frac{v_o}{v_i}$ and $A = \frac{v_o'}{v_i}$ or implies $v_i = \frac{v_o'}{A}$. So, if you substitute this here this A' is equal to this v_i is $\frac{v_o'}{A}$.

So, this is $A \frac{v_o}{v_o'}$. So, if I first, find out $\frac{v_o}{v_o'}$ you can substitute here. So, in order to find out $\frac{v_o}{v_o'}$ what is v_o in terms of v_o' voltage division $v_o' \frac{Z_2}{Z_1+Z_2}$. This is equal to Z_2 is nothing, but $R_2 + \frac{1}{SC_2}$ divided by Z_1 is simply $R_1 + R_2 + \frac{1}{SC_2}$ into v_o'. So, if you simplify this 1 plus SR_2C_2 in the numerator SC_2 SC_2 will get cancelled.

So, this is equal to $1 + S(R_1 + R_2)C_2$ into v_o'. We can further simplify this if I take SR_2C_2 in the numerator common then this will be $1 + \frac{1}{SR_2C_2}$. And in the denominator if I take $SC(R_1 + R_2)C_2$, and this will be $1 + \frac{1}{SC(R_1+R_2)C_2)}$. Now, this S S$C_2$ C_2 get cancelled. So, this will be now into of course, $\frac{R_2}{R_1+R_2} \frac{[1+j\frac{f}{f_1}]}{[1+j\frac{f}{f_O}]} v_o'$ So, then what will be this term? This term becomes now $s = j\omega = j2\pi f$. So, we will get $j\frac{f}{f_1}$ and in the denominator we will get $j\frac{f}{f_o}$ into v_o'. If I choose this $R_2 \gg R_1$ then $\frac{R_2}{R_1+R_2} \approx 1$. So, this is approximately equal to $\frac{[1+j\frac{f}{f_1}]}{[1+j\frac{f}{f_O}]} v_o'$ this is v_o. So, what is $\frac{v_o}{v_o'}$, that we are going to substitute here? So, implies $\frac{v_o}{v_o'} = \frac{[1+j\frac{f}{f_1}]}{[1+j\frac{f}{f_O}]}$.

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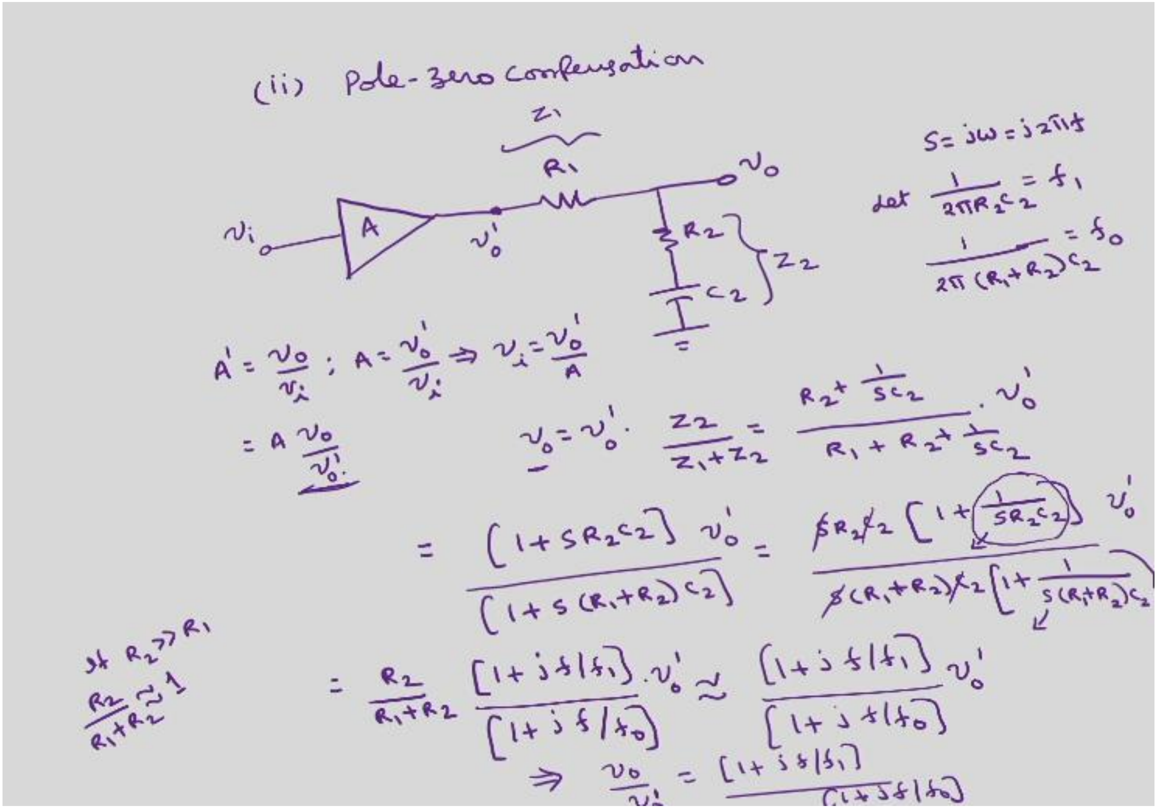

So, if I substitute this $\frac{v_o}{v_o'}$ here $A' = A\frac{[1+j\frac{f}{f_1}]}{[1+j\frac{f}{f_o}]}$. What is A in terms of open loop gain? Assuming that 3 break frequencies is $\frac{A_{OL}}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}\frac{[1+j\frac{f}{f_1}]}{[1+j\frac{f}{f_o}]}$. So, this is we are going to choose this f_1 such that this will cancel with the first break frequency. So, that this output $\frac{A_{OL}}{(1+j\frac{f}{f_o})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$. Here $f_o < f_2 < f_3$, f_1 is get cancelled.

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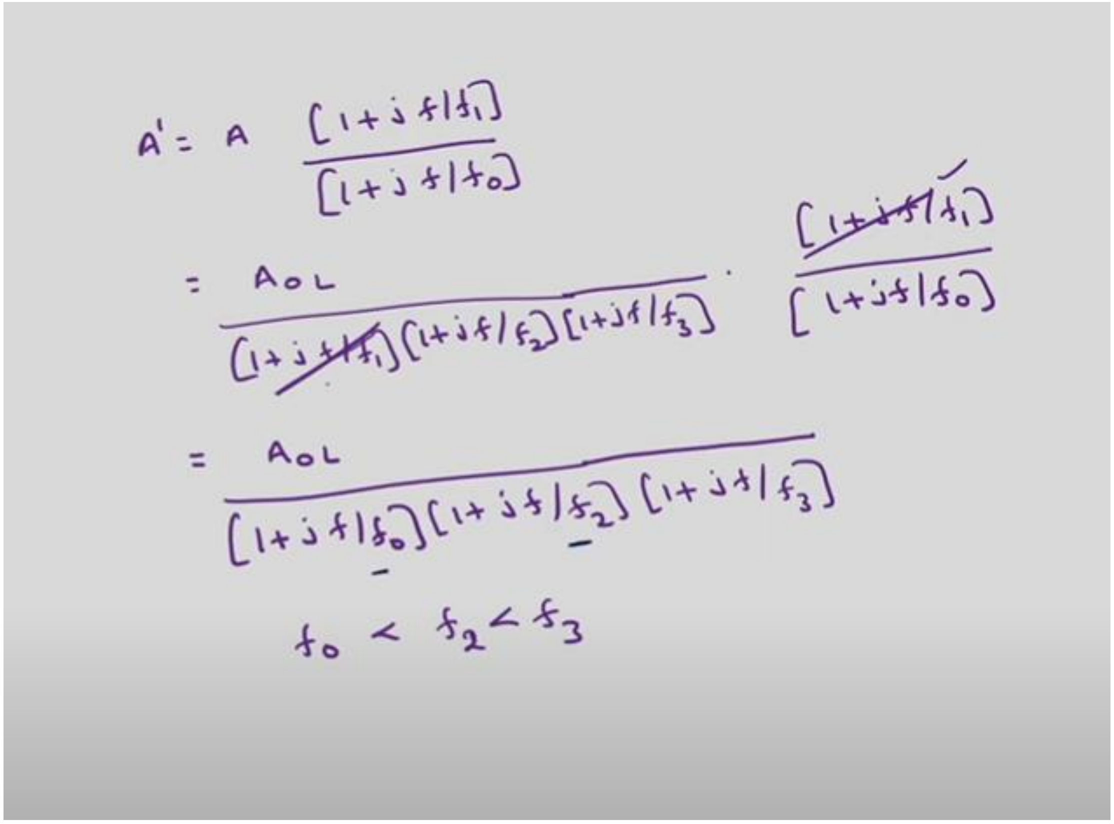

Now if I plot this frequency response then bandwidth will increase and also this 20dB side slope will be there up to the frequency f_2. I will plot on the same graph this is compensated system with dominant pole compensation. Now, if I plot for this pole 0 compensation if I assume that this is the frequency f_o. So, the next frequency is f_2 f_1 is going to get cancel f_o to f_2 it will go with $20dB/dec$ slope.

So, this will go up to f_2. So, this is the frequency response of pole 0 compensation. Now compared to this dominant pole this was the bandwidth now the bandwidth will be this much bandwidth is increased. And at the same time this $20dB/dec$ slope will be there up to f_2 point. So, there will be no stability issue.

So, these are the two types of the external compensations pole 0 compensation and dominant pole compensation. There are some applications where we need only the lower frequencies such as the instrumentation applications. And applications where high frequency compensation is not required such as if I take pressure variation temperature variation and even if you take the biomedical signals the ECG, EEG variations they are slow varying signals. If we consider the pressure, temperature etcetera they are slowly varying signals. Here we do not need this external compensation.

So, in that case normally we will provide the compensation internal to the operational amplifier. So, the other type of compensation is called internal compensation that is the resistor and capacitor will be fabricated inside the operational amplifier itself. So, if I consider the IC 741 this is internally compensated op amp. If I take the frequency response of this IC 741 say 10^5 gain this will be somewhere 10^{-1} this is $10MHz$. So, this is 10^{-1}, and this is 10 this axis is gain this is bandwidth.

So, the gain bandwidth product will be constant. The gain bandwidth product of 741 is $1MHz$, this is called GBW. It is clear that here $10MHz$ is the bandwidth this is the bandwidth and gain is $10 \times 10^{-1} MHz = 1MHz$. If I consider 10^4 gain here this will occur at $100Hz$. So, what is the gain bandwidth product $GBW = 10^4 \times 100 = 1GHz$.

You take any point the gain bandwidth product will be constant that is of the order of $1GHz$ for 741 IC. For a given gain there is a maximum limit on the bandwidth beyond that we cannot process by using the given operational amplifier. So, this is the limitation of this operational amplifier at small signals. So, this gain bandwidth product is high frequency limitations this gain bandwidth product is high frequency limitation for small signals. So, small signals are normally called as the signals of amplitude mV or μV.

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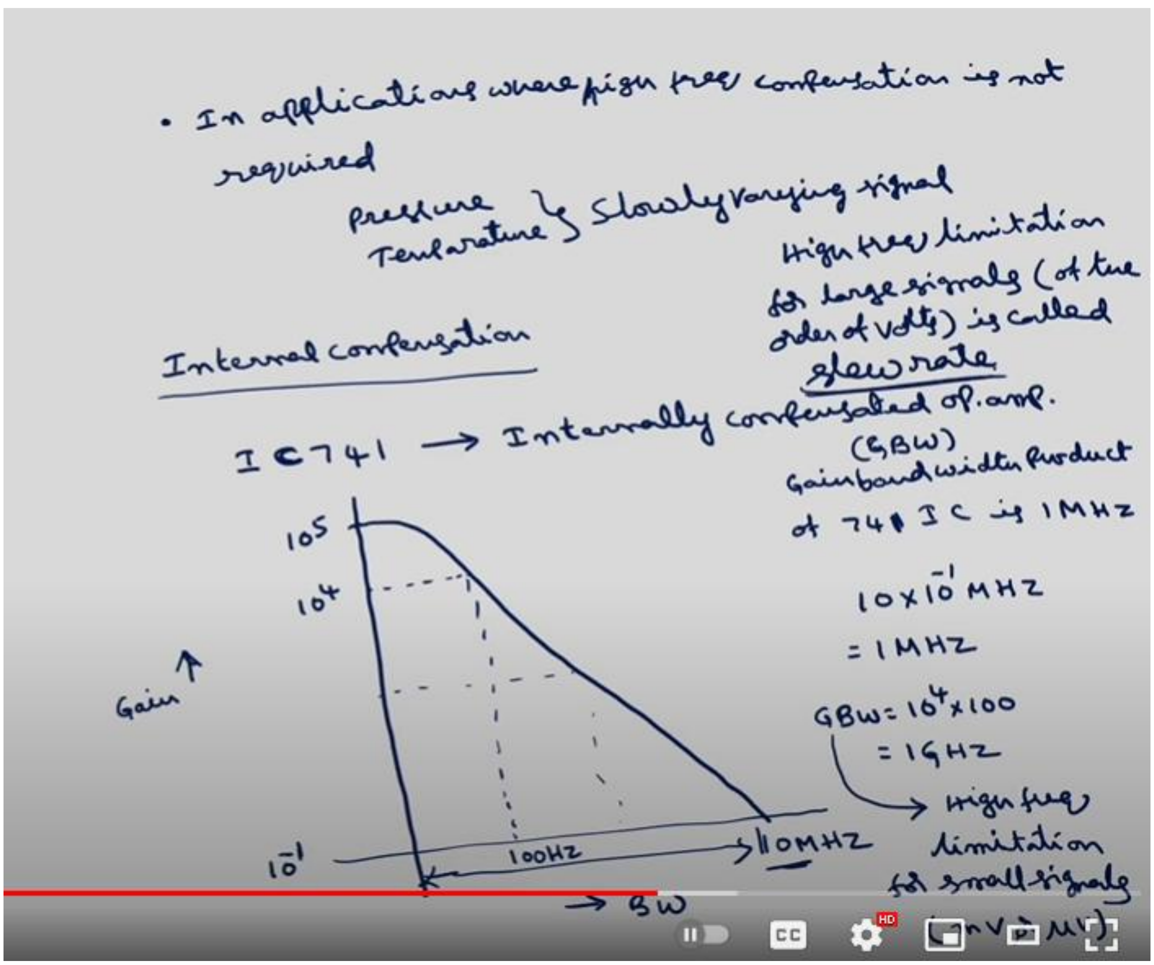

Whereas, the same high frequency limitation is there for the large signals also. So, that high frequency limitation for the large signals for large signals normally of the order of volts is called as slew rate this is another important parameter of operational amplifier. So, now we will discuss the slew rate. Slew rate is defined as the maximum rate of change of the output of half amp with respect to time. So, slew rate $SR = \frac{dv_o}{dt}|_{max}$.

If I consider say the voltage follower circuit. So, whatever the input should be equal to output is voltage follower. So, if I give the input as step this is the input v_i, if I give input as step signal output will not be a step signal output it will go to if this is v volts this amplitude what is v say. Then the output will be it will go to v with some slope it will finally, reach v after some time, but before that there will be a linear variation the slope of this one is slew rate. So, normally slew rate will be measured in $v/\mu sec$ is the unit of slew rate.

Suppose if slew rate is given as $1v/\mu sec$ the meaning of this one is $1v/\mu sec$. The meaning of this one is the output either rises or falls not beyond $1v/\mu sec$, that means, the output falls or rises not beyond $1v/1\mu sec$. For an ideal operational amplifier slew rate should be infinity means output simultaneously changes with the input. That is here if I give the input as this step signal v_i output also immediately will get step signal this is of v volts this is also of v volts, but this is the ideal case. For practical case it will take some time to get the output voltage which is equal to input voltage.

So, practically the slew rate varies from 0.1 to 1000 $v/\mu sec$ this is normal range of practical op-amp.

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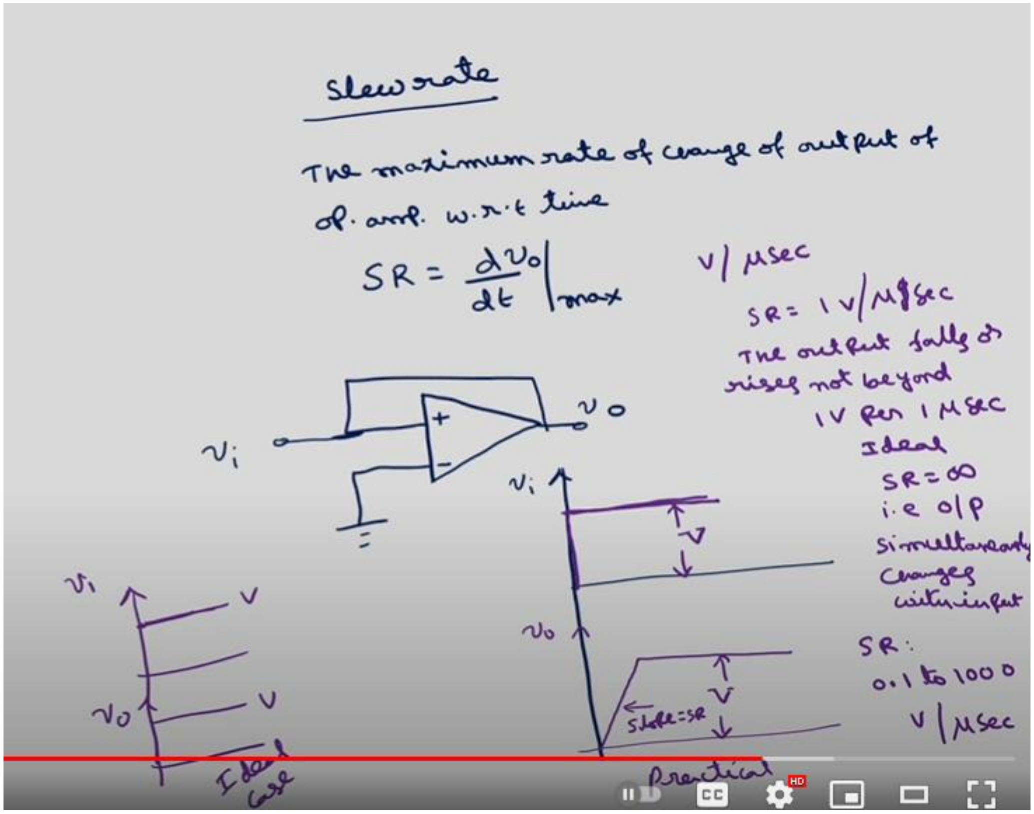

Now, to have a better understanding of this slew rate, if I consider the input $v_i = v_m sin\omega t$, and we will consider the voltage follower only. So, output is equal to input for voltage follower why because the most of the operational amplifier this specification will be given as a slew rate for unity gain. So, normally slew rate will be specified for unity gain that is why I am considering the voltage follower.

Then $v_o = v_m sin\omega t$. Then what is $\frac{dv_o}{dt} = v_i = v_m \omega cos\omega t$, and slew rate is defined as the maximum rate of change of the output $\frac{dv_o}{dt}|_{max}$. So, what is the maximum value of this one? The maximum value of $cos\omega t = 1$. So, this will be simply $v_m \omega$, this is equal to $v_m 2\pi f$ or from this we can find out the maximum frequency that will be allowed is maximum frequency $f_{max} = \frac{SR}{2\pi v_m}$. So, if SR is in $v/\mu sec$ into 10^6, here SR will be v/sec.

Now, because 10^6 have written now here this SR will be $v/\mu sec$ and if you simplify this value this will be around $\frac{SR}{6.25 v_m} 10^6 Hz$. So, what is this f_{max}? This is called maximum power bandwidth this f max is called maximum power means. So, this op-amp can process up to f_{max} only without any distortion op-amp gives undistorted output for frequencies up to f_{max}. If I apply the input frequency above this f_{max} there will be distortion undistorted output in the sense the shape of the signal remains same.

So, if I apply the frequencies beyond this f_{max} there will be distortion in the output. So, this slew rate decides what is the maximum frequency to get undistorted output this is one definition. The other way if I fix this f_{max} to a value then this slew rate will give the maximum undistorted output the amplitude of maximum undistorted output at a given frequency and to get a given slew rate then it will give the maximum undistorted amplitude of the signal. There are two ways we are going to apply the input to this signal $v_i = v_m sin 2\pi f t$. So, this slew rate decides what is the maximum frequency that we can apply so, that the output will be undistorted the maximum frequency.

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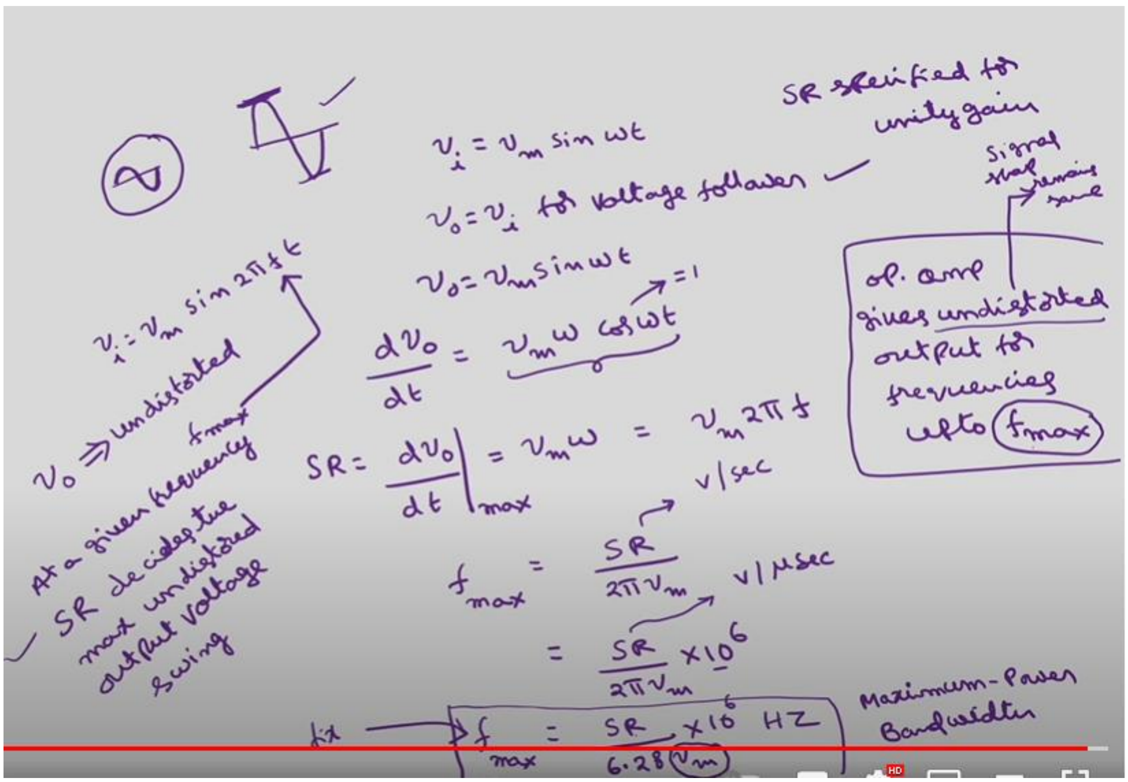

On the other hand if I fix the frequency this slew rate at a given frequency slew rate decides the maximum undistorted output voltage swing. If the input is this output is what is the maximum value of this amplitude what is the maximum value of this amplitude without changing shape of this input. Input is sinusoidal signal output also should be exactly same sinusoidal signal with some maximum magnitude limit this will be decided by the slew rate. If I fix this one then this slew rate will decide the maximum frequency of the input signal that will cause undistorted output this is about the slew rate. So, we will consider the examples in the next lecture. Thank you.